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Finite Element Modeling And Analysis Of Gasket On Circular Bolted Flange Connection

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Abstract- In the piping industry, there are several problems that continue to receive a considerable amount of research attention, particularly in the area of bolted-flanged joint design. Two problems that are critical in bolted flanged joint design are strength of the joint and leakage. The first problem has been studied since the 1920s for metallic joints with a general consensus on the available solution well established. The second problem has been studied for almost an equally long period yet leakage analysis continues to be the subject of much study, as evident by the number of articles published in the past quarter century.Here, an analysis is presented that can be used in design formulations for the detection of leaks for a specified pressure. There are many parameters that influence joint leakage (bolt load, internal pressure, gasket material, flange stiffness, flange geometry, contained medium, etc.); of these parameters, boltload, flange stiffness, internal pressure, and gasket material appear to be most critical.

Keywords- Coupling, Ansys, FEM analysis, stress, deformation

I. INTRODUCTION

Half of a typical raised face bolted flange is depicted in Fig. 1.1. This is one of the symmetries that can be exploited in modeling bolted flanged joints. There is another symmetry that can be used to reduce the size of the model, the wedge model shown in Fig. 1.

Also, leakage can be analyzed using an axisymmetric model, taking into account proper boundary conditions, without loss of practical accuracy.Gaskets play an important role in the sealing performance of bolted flange joints, and their behaviour is complex due to nonlinear material properties combined with permanent deformation. The variation of contact stresses due to the rotation of the flange and the material properties of the gasket play important roles in achieving a leak proof joint Flanged joints with gaskets are very common in pressure vessel and piping systems, and are designed mainly for internal pressure. These joints are also used in special applications such as in nuclear reactors and space vehicles.The connection of a fuel duct to a rocket engine is a typical application of these joints in space vehicles. Prevention of fluid leakage is the prime requirement of flanged joints. Many design variables affect joint performance and it is difficult to predict the behaviour of joints in service. The complexities associated with the analysis of bolted flange joints with gaskets are due to the nonlinear.

Behaviour of the gasket material combined with permanent deformation. The material undergoes permanent deforma- tion under excessive stresses. The degree of elasticity (stiffness) is a function of the compressive stresses, which act on the gasket during assembly and after it is put into service. It is commonly recognized that gasket stiffness has a predominant effect on the behaviour of the joint because of its relatively low stiffness.Another inherent problem with bolted joints is flange rotation and contact stresses. These are caused by the bolt pre-load and increase when the joint is subjected to internal pressure. The ASME code has made an attempt to correct this problem by adding a rigidity constraint 'J' based on the fixed rotation. This may not be adequate, as the rotation of the flange is not a unique value. Flange rotation causes variable compression across the gasket from the inner radius to the outer radius. Due to the variation in compression, the contact stresses also vary along the radius.In the present work, a finite element (FE) model for finding the contact stresses in a gasket has been developed.The sealing performance of different gasket models with varying loading and operating conditions has been studied. The distribution of contact stress on the gasket for different loading conditions has also been studied.

2. Bolted flange connection

A bolted flange connection is a complex mechanical system whose components must be selected and assembled properly to provide reliable sealing over a wide range of operating conditions. All of the various components of the assembled bolted flange connection are important to the proper operation of the joint. The components consist of the piping, or vessels, the flange(s), the gasket(s) and bolts. In addition to the components themselves, the joint design and assembly are critical to the long-term operation of the joint.A=Fastener (A1=Bolt, A2=Washers, A3=Nut); B=Flange; C=Gasket

A gasket is used to create and retain a seal between two surfaces that are stationary – as opposed to a dynamic seal which is between two moving parts (ex: rotating or reciprocating). These static seals aim to provide a complete physical barrier to contain the fluid within the pipe or vessel and any potential leak paths a) between the surfaces of the flange or b) through gasket material itself. The application may be intended to remain closed indefinitely (such as a pipeline) or in some cases, repeated opening and closing is required (such as a door seal).

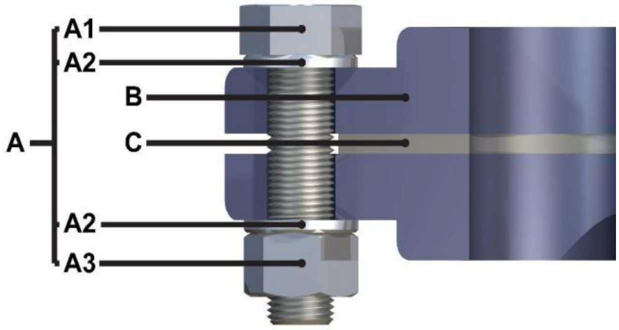


Fig. 1: Bolted flange connection (arthomson.com)

To achieve a successful seal, the gasket must be resilient enough to conform to any irregularities in the mating surfaces. The gasket must also have sufficient tensile strength to resist sealing element squeezing or flowing out between the mating surfaces as a result of pressure or other forces in the system. The seal is created by the clamping forces acting upon the gasket surface, compressing the gasket and causing the gasket to conform to and fill, flange imperfections. The conformance of the gasket material to the bolted flange connection surface under the compressive load (contact pressure) fills any leak paths and prevents the escape of the contained fluid from the bolted flange connection within a specified leakage rate (or tolerance).

The function of a gasket is to create and maintain a static seal between two stationary, imperfect surfaces of a mechanical system, designed to contain a wide variety of liquids or gases. The gasket must be able to maintain this seal under all the operating conditions of the system including extremes of temperature and pressure.The performance of the gasket is affected by a number of factors. All of these factors must be taken into consideration when selecting a gasket.

3. Flange Description

The flange geometry and dimensions used in the analysis were extracted from Ref. [9] and are shown in Fig. 2. The flange is a raised face flange typically used in high pressure applications. The flange face nearest the bolt holes is raised 3 mm, which allows rotation of the flange. The flange is constructed of steel with young's modulus of 200 GPa and Poisson's ratio of 0.3.

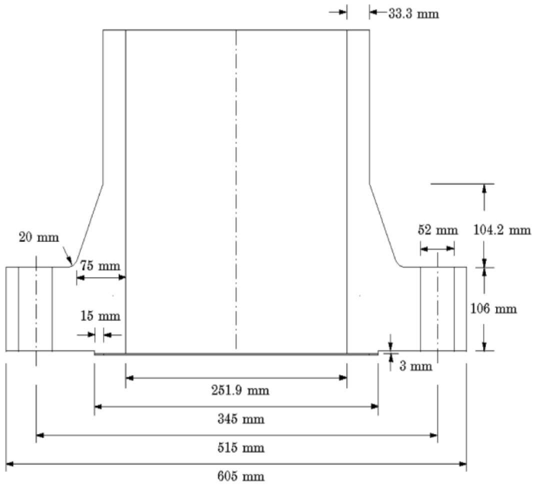


Fig. 2: Flange geometry and dimensions (Estrada, 2015)

2.FEM model

In its most basic form, FEM is an approximation method that subdivides a complex problem space, or domain, into numerous small, simpler pieces (the finite elements) whose behavior can be described with comparatively simple equations.The basic concept in the physical interpretation of the FEM is the subdivision of the mathematical model into disjoint (non-overlapping) components of simple.Finite Element Modeling (FEM), also known as Finite Element

Analysis (FEA), is a numerical method utilized to predict the performance of structural, thermal, fluid, electromagnetic and other physical systems. The method requires that the component being studied be broken into discrete elements, resulting in a finite element mesh. The simple equations that describe the individual elements' behavior are then assembled into a larger system of equations that models the entire problem. Depending on whether nonlinear effects are present the resulting system of equations is solved with a direct or iterative solver.

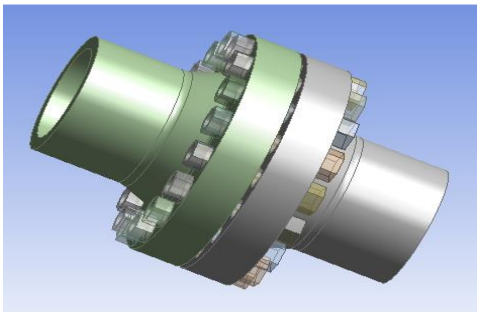
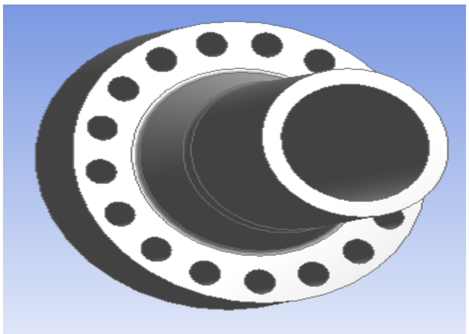
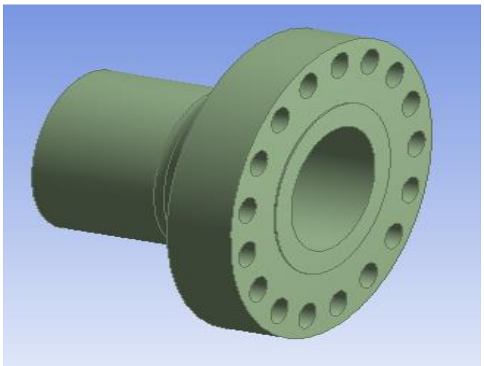


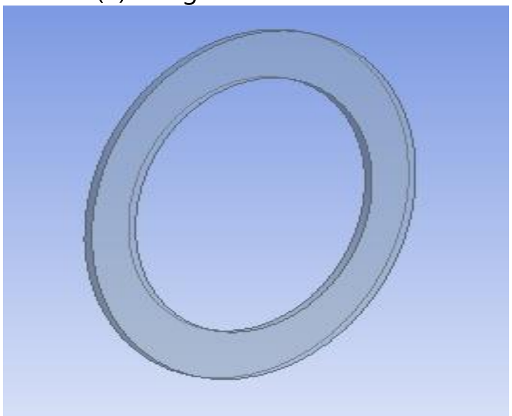
Fig. 3: FEM model of bolted flange coupling (self-made)



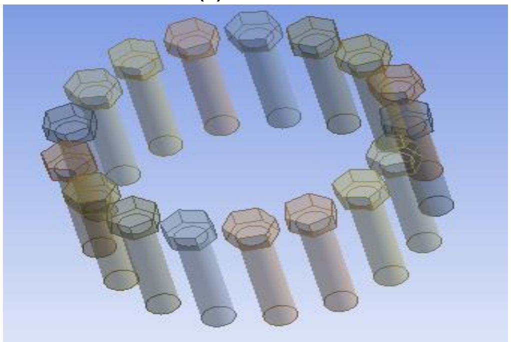
(a) Flange A



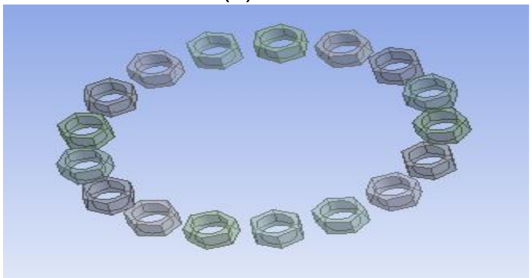
(b) Flange B



(c) Gasket



(d) Bolt



(e) Nut

Fig. 4: Exploded view of bolted flange coupling (self-made)

Meshing

A SOLID45 structural element is used to model the flange, bolt, gasket and pipe; three-dimensional 'surface-to-surface' CONTA174 contact elements, in combination with TARGE170 target elements are used between the flange face and gasket, bolt shank and flange hole, the top of the flange, and the bottom of the bolt in order to simulate contact distribution for both structural and thermal models. A 3-D interface element INTER195 is used as a special gasket element for meshing of the spiral wound gasket, which is compatible with SOLID45 structural elements. The gasket meshing requires two faces i.e.source and target faces. The source face which is the top area of the gasket is meshed with SHELL 63 elements.

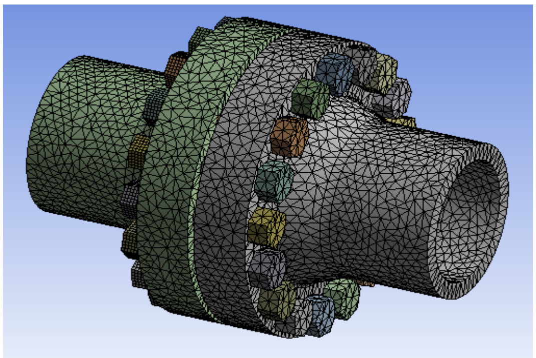


Fig. 5 Mesh model of bolted flange coupling (self-made)

Boundary conditions and joint loading

Boundary conditions are constraints necessary for the solution of a boundary value problem. A boundary value problem is a differential equation (or system of differential equations) to be solved in a domain on whose boundary a set of conditions is known.In FEA, the physical domain under analysis is subjected to constraints, called boundary conditions, for convergence of the solution to reasonable results.The bolt load computed is smeared over the bolt hole upper surface as a normal pressure, as shown in Fig. 3.6. This is the load applied at the beginning of the analysis, the seating condition.

In this case, there should be no contact loss during the loading and the reacting gasket pressure should be larger than the minimum effective seating pressure, y. The initial bolt load is applied as 15KN. In order to achieve the required bolt-preload, displacement constraint is applied in the y-direction at the bottom of the bolt shank. After application of bolt pre-load, internal pressure is applied at the inner surface of the pipe. Maintaining the internal pressure, axial load, and end cap loading is applied at the end of the pipe. Bending load is applied, after internal pressure and axial loading, away from the flange joint center as per the methodology adopted in the experimental study.Boundary condition for the flange joints is shown in Figure 6.

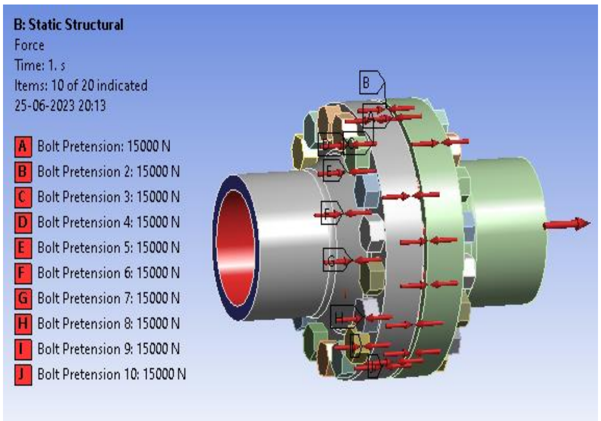


Fig. 6: Boundary condition applied on bolted flange coupling (self-made)

Table 1: Boundary condition

Loading case	Loading type	Loading magnitude
Loading case 1	Bolt up force, design pressure	DP-15.3 MPa, PT-15KN
Loading case 2	Bolt up force, design pressure and axial force	DP-15.3 MPa, PT-15KN, AL-75KN
Loading case 3	Bolt up force, design pressure, axial force and torque	DP-15.3 MPa, PT-15KN, AL-75KN, Torque-505nm
Loading case 4	Bolt up force, design pressure, axial force, torque and bending load	DP-15.3 MPa, PT-15KN, AL-75KN, Torque-505nm, BL-9.75KN

IV. RESULTS AND DISCUSSION

1.Stresses in bolted flange coupling

In this section, stresses due to different loading conditions in bolted flange coupling are plotted.

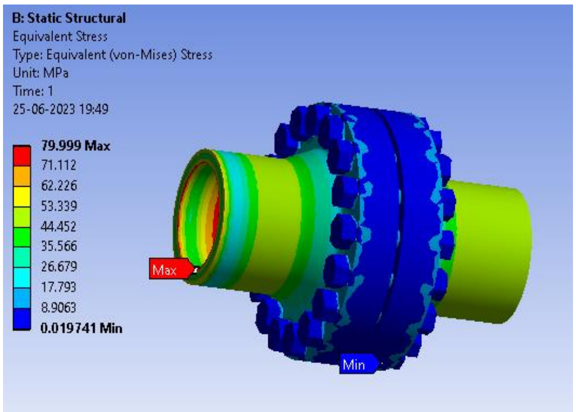


Fig. 7: Stresses in bolted flange coupling for loading case 1

A bolted flange coupling is a mechanical connection used to join two shafts together. It is commonly used in various industrial applications, especially in the assembly of pumps, compressors, and other rotating machinery. The performance and integrity of a bolted flange coupling depend on various factors, including the loading conditions it is subjected to. Different loading conditions can induce different types of stresses in the coupling, which must be considered for its design and analysis.In a bolted flange coupling, various types of stresses can develop due to the mechanical forces and loads it experiences during operation. These stresses can affect the integrity and performance of the coupling, and they need to be considered during design and analysis. The maximum stress is obtained as 79.99 MPa.

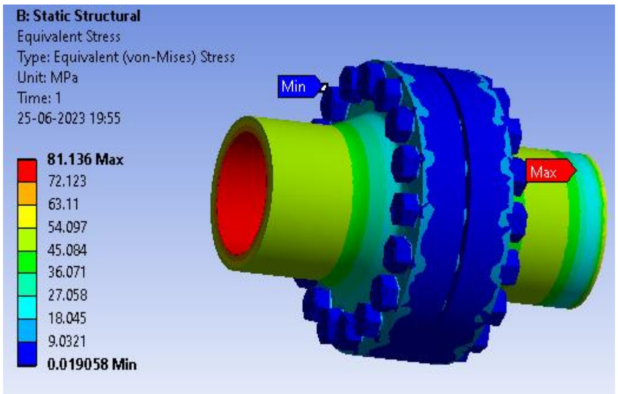


Fig. 8: Stresses in bolted flange coupling for loading case 2

In the context of bolted flange couplings, bolt-up force, design pressure, and axial force are important factors that influence the stresses in the coupling. The bolt-up force directly affects the tensile stress in the bolts. When the bolts are tightened, they experience an axial (tensile) load. The magnitude of this load depends on the bolt-up force and the number of bolts used in the coupling. Properly controlling the bolt-up force is crucial to ensure that the bolts can withstand this tensile load without failing.Design pressure primarily affects the internal stresses in the flange and the gasket. The higher the design pressure, the more significant the compressive forces acting on the gasket and the flange faces. These forces can result in higher contact stresses between the gasket and the flange faces. To ensure a reliable seal, the flange and gasket materials must be selected to handle the design pressure without exceeding their allowable stresses.

Axial forces, when present, can contribute to additional tensile or compressive stresses in the bolts and the flange. These stresses are in addition to the bolt-up force and can affect the overall integrity of the coupling. Engineers must consider these axial forces in the design to ensure that the coupling can handle the combined effects of bolt-up force, design pressure, and axial force without failure. The maximum stress is obtained as 81.13 MPa.

The key challenge in designing a bolted flange coupling is to ensure that the combination of these forces does not exceed the material limits of the components (bolts, flange, gasket) and that the gasket maintains a proper seal under the applied loads. Engineers use stress analysis, material selection, and appropriate torque values during assembly to achieve this goal. Additionally, the design must consider factors like safety margins and potential variations in operating conditions to ensure the reliability and longevity of the coupling. Properly managing these factors is essential for preventing leaks, ensuring safety, and maintaining the overall integrity of the system.

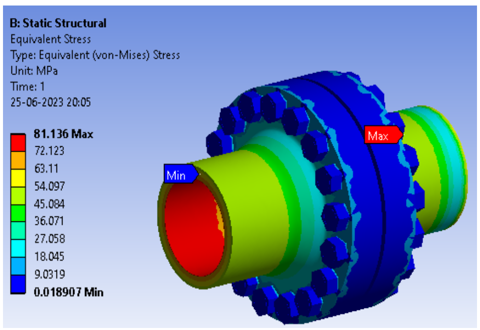


Fig. 9: Stresses in bolted flange coupling for loading case 3

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The maximum stress is obtained as 81.13 MPa. The bolt-up force, which is the axial load applied to the bolts during tightening, contributes to tensile stress in the bolts. If this force remains constant, the tensile stress in the bolts will also remain constant.Design pressure primarily affects the internal stresses within the flange and gasket. Assuming a constant design pressure, the compressive stress on the gasket and the contact stresses between the gasket and the flange faces will remain unchanged.

If the axial force applied to the coupling is held constant, it will contribute to either tensile or compressive stress in the bolts, depending on its direction. If the magnitude of this force remains the same, the associated stress will also remain constant. Torque applied during tightening generates axial load in the bolts, leading to tensile stress. If the torque is applied consistently and is not changed, the tensile stress due to torque will remain consistent as well.

So, if all of these factors are fixed and unchanged, the stress within the coupling will remain the same under those specific conditions. However, it's important to note that in practical applications, these factors are often subject to variations, and engineers need to account for these variations in their designs and analyses to ensure the coupling's reliability and safety under various operating conditions.

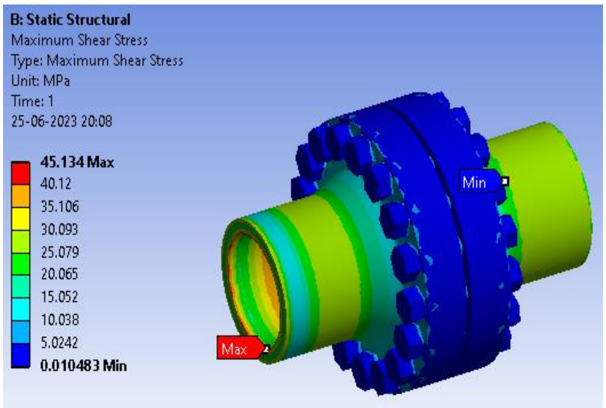

Fig. 10: Stresses in bolted flange coupling for loading case 4

Under, bolt up force, design pressure, axial force, torque and bending load, the maximum stress is obtained as 45.13 MPa. A maximum stress of 45.13 MPa suggests that the coupling has been analyzed, and this stress level has been determined to be within acceptable limits for the material and design of the coupling under the combined effects of bolt-up force, design pressure, axial force, torque, and bending load.

A maximum stress of 45.13 MPa indicates the highest stress level experienced by the components of the bolted flange coupling, which includes the bolts, flange, and possibly the gasket material.To assess the safety of the coupling, engineers typically compare the maximum stress to the material's allowable stress. If the maximum stress is well below the allowable stress, it suggests that the coupling is designed with a margin of safety and is less likely to experience failure.It's important to note that the maximum stress is obtained by considering the combined effects of various loading conditions, including bolt-up force, design pressure, axial force, torque, and bending load. This comprehensive analysis accounts for the complex interactions of these forces within the coupling.

The calculated maximum stress value is used to verify that the coupling is designed to meet the safety and performance requirements for its intended application. Engineers will have determined the appropriate design parameters, such as bolt size, material properties, and gasket specifications, to achieve this result.While this analysis provides valuable insights into the coupling's behavior under specific conditions, it's essential to continue monitoring the coupling's performance in real-world operation and consider factors like fatigue, temperature variations, and maintenance practices to ensure its long-term reliability.

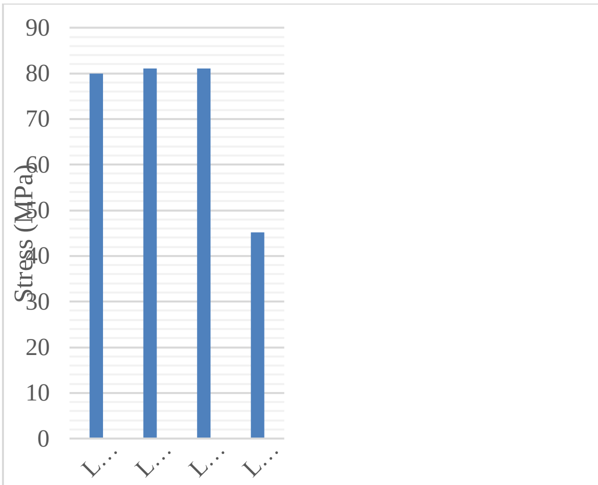

Fig. 11: Stresses in bolted flange coupling for different loading case

V. CONCLUSION

Stress in the radial direction within a coupling, especially in the gasket, can increase under combined loading conditions. Combined loading refers to the simultaneous application of multiple types of mechanical loads, such as axial loads, bending moments, torque, and design pressure.

These different loading conditions can interact with each other, leading to complex stress patterns within the coupling components, including the gasket. Axial loads, whether tensile or compressive, can introduce radial stress components in the gasket and other coupling components. When axial loads are applied off-center, they can cause bending, which adds to the radial stresses. The maximum stress is observed in loading case 1 and minimum in loading case 4.

Bending loads, including moments that create angular deflection in the coupling, can induce both axial and radial stresses. These bending stresses vary with the distance from the point of loading, leading to radial stress gradients within the coupling. Torque applied to the bolts creates axial loads, resulting in radial stresses in the gasket due to the bolt-up force. Additionally, if the coupling experiences torsional loading, this can also introduce radial stresses. Design pressure, representing internal pressure within the piping or vessel, applies radial stress on the gasket. When combined with axial and bending loads, it can affect the overall stress state within the gasket, leading to radial stress variations.

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